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MANAGEMENT OF MATERIAL FLOWS IN THE STEEL INDUSTRY. CASE STUDY: ELABORATION OF STEEL IN AN ELECTRIC ARC FURNACE

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Abstract**:** *Worldwide, the activity of all steel companies must comply with the recommendations set out in the Best Available Techniques Reference (BREF), documents related to the Best Available Techniques (BAT) specifications issued for iron and steel production. For this reason, the main BAT specifications for the management of raw materials and production residues/waste, applied to companies producing steel in electric arc furnace, have been identified in this paper. The case study was carried out for a steel mill equipped with an electric arc furnace to present the management of production material and waste streams, also with the objective of identifying the degree of compliance with specific BAT techniques. Based on the findings, the authors developed a series of proposals to improve material management within the steel company for which the case study was conducted.*

Key words: *Best Available Techniques (BAT), electric steel mill, material flow management.*

1. INTRODUCTION

Today, electric arc furnaces worldwide are increasingly present in the manufacturing flows of modern steel mills; this is due to the possibility of direct melting of ferrous waste. Electric furnaces allow for a load consisting of 100% ferrous metal waste, such as internal scrap, steel scrap from processors and users of steel products (such as vehicle builders, metal constructions) and post-consumer waste (for example: end-of-life vehicles, demolition waste, scrapping machinery, etc.). In industrial practise, in addition to scrap metal, an iron sponge/direct reduced iron (DRI) is also introduced into the electric arc furnace [1,2], it is produced from iron ore and/or small and powdery waste containing iron (steel mill dust, blast furnace dust, mill scale, slurry from agglomeration plants, waste from other industries such as red sludge – bauxite processing, or pyritic ash – resulting from the process of obtaining sulfuric acid, etc.).

Figure 1 shows the process of steel production in the electric arc furnace with eccentric bottom tapping (Eccentric Bottom Tapping - EBT), a representation made after the reference study [3-9].

At the global level, it is recommended that activities carried out in steel companies are aligned with recommendations aimed at preventing and controlling industrial emissions and environmental impacts caused by industrial installations, which are set out in the BREFs for the recommended BAT technologies.

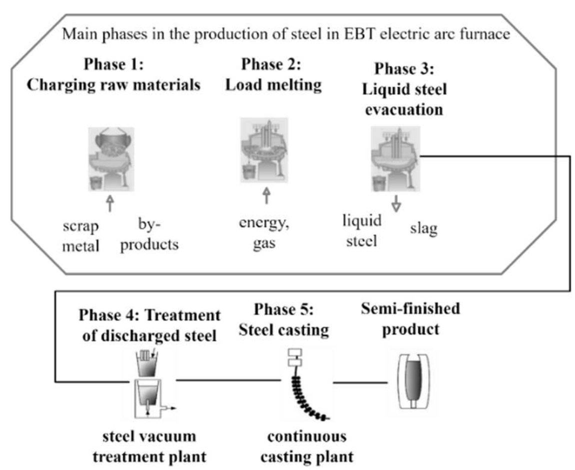

Fig. 1. Presentation of the elaboration flow – second treatment – continuous steel casting, adaptation according to [3-9]

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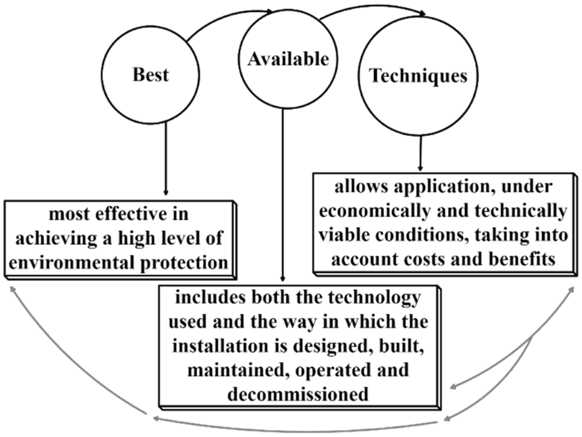

Fig. 2. Definition of BATs according to the European Union Industrial Emissions Directive [10]

Table 1

Variation limits for electric arc furnaces in the European Union [4]

Raw materials [kg/t liquid steel]		**Consumption**	
Scrap metal	1039 – 1232	Electricity	404 – 748 kWh/t liquid steel
Cast iron waste	0 – 153	Gas	50 – 1500 MJ/t liquid steel
Direct reduced iron (DRI)	0 – 215	Cooling water	1 – 42.8 m^3/t liquid steel

BATs are proven and advanced techniques that aim to prevent and control industrial emissions and the impact caused by industrial installations on the environment, their development being carried out on a scale that allows their application under viable conditions from an economic and technical point of view [7,10,11].

The European Union's Industrial Emissions Directive contains the specifications given the name Best Available Techniques (BAT); these are shown in Figure 2 and have been identified after the literature review [10].

According to the BAT references in the steelmaking process of the arc furnace steelmaking process, the variation limits imposed for raw materials, energy consumption, gas, and the amount of liquid steel developed in a single process run are given in Table 1.

In previous research on the steel life cycle [12], raw material input and consumption related to a process flow within a steel producing company have been found to fall within pre-established limits of variation worldwide for the production of one tonne of liquid steel, which is also identified and found in this case.

Currently, worldwide steel production in electric arc furnaces is limited by the availability of steel scrap and the potential impact on steel quality [13].

The purpose of the paper is to identify the BAT techniques set out in the BREFs for steel producing companies and to present how they are applied in a steel mill. In the paper, the authors also detail the management activities of raw material flows (scrap steel and scrap metal, owned or delivered to the company by authorised suppliers), in order to identify the main problems faced by the steel company concerned. To solve the identified issues, some solutions focused on improving material flows that would generate a potential increase in the company's steel production were developed.

2. RESEARCH METHODOLOGY

This article aims to present a synthesis of the main techniques and requirements according to BAT to produce iron and steel production, focussing on the management of secondary raw materials and production waste; it was identified how they are applied in a steel mill in Romania that owns an electric arc furnace.

2.1 Recommendations on the management of secondary raw materials and production waste according to the BAT rules

Management of secondary raw materials (scrap metal)

The handling operation is essential in the secondary raw material management process; its implementation minimises the possibility of any non-magnetic material (stones, wood, or non-ferrous metals) being introduced into the manufacturing flow. During the handling operation of secondary raw materials (scrap metal, end-of-life vehicles, etc.), dust and noise emissions are frequently generated for which mitigation measures can be taken or preventive actions can be established to minimise them.

The sorting operation is adjacent to the scrap metal handling operation and is carried out to reduce the risk of including hazardous elements (in which case we want to refer to the radioactivity of waste) or undesirable (large quantities of non-ferrous metals that can downgrade steel charge).

Controlling the radioactivity of metal waste is a matter of prime importance for the steel industry that relies on waste streams, and therefore this aspect has been studied in detail by a group of experts from the United Nations Economic Commission for Europe (UNECE). The UNECE Group of Experts developed in 2006 a framework of recommendations and examples of good practise based on existing national, regional, and international instruments and standards [14].

The aspects provided in the framework of the report "Recommendations regarding monitoring and response procedures for radioactive metal waste" include [14]: Monitoring and response procedures for radioactive scrap metal; Capacity-building strategy for monitoring and response procedures.

Radioactivity to scrap metal can occur in several ways, some of the causative situations occur in [14]:

- Demolition or decommissioning of industrial plants processing raw materials containing natural radionuclides;
- Decommissioning of nuclear and other installations;
- Loss of radioactive sources that may subsequently encounter scrap metal;
- Demolition of facilities where radioactive sources have been used;
- Inclusion of old radioactive devices in waste.

In industrial practise, scrap metal and metal waste are most often stored directly on the ground for a long time, causing a high level of soil pollution with heavy metals and hydrocarbons. It is recommended that storage be done in sheds, on concrete platforms, or outdoors, but not directly on the ground, to prevent heavy metal contamination.

The metal waste streams once entered the company's gate require preliminary preparation/batch operations (cutting/breaking of large, oversized waste, and briquetting/compaction of small scrap waste). It is recommended to avoid or minimise the duration of storage of metal waste. Figure 3 shows the flows corresponding to the handling and storage of secondary raw materials by steel companies whose activity is based on the use of scrap metal in the steelmaking process.

Radioactivity testing, handling, sorting and processing of own and external scrap metal must be carried out thoroughly following BAT recommendations so that steel companies attest to compliance with the quality requirements necessary for the use of iron-containing scrap metal in production streams.

Production waste management

During the manufacturing process of steel semi-finished products, a wide range of production waste (slag, dust, solidified liquid steel, etc.), and they must be properly managed in order not to harm the environment. Most residues and waste generated within a steel company producing semi-finished steel products contain iron, which is why they can be used as secondary raw materials in the processes in which they were generated (according to the principles of circular economy). Table 2 shows the main waste generated in the process of producing one tonne of liquid steel and the corresponding variation limits for electric arc furnaces in the EU.

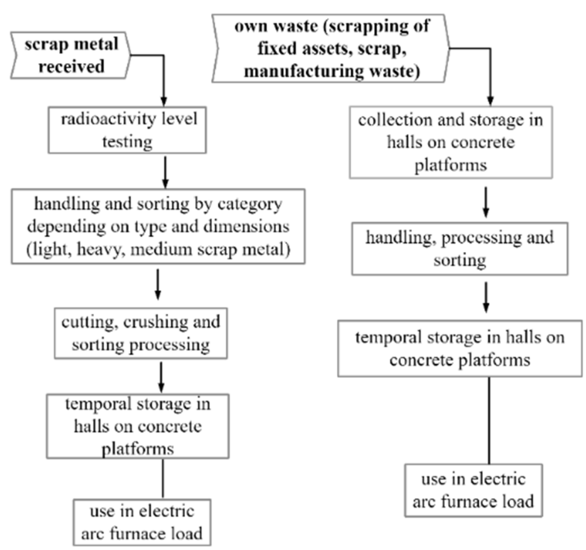

Fig. 3. Appropriate handling and storage flows of secondary raw materials

Table 2

The main residues and wastes generated in the production of a ton of liquid steel [4]

Production waste	Quantity generated [kg/t liquid steel]
Slag	10 – 80
Dust from flue gas cleaning	10 – 30
Refractory wastes	1.6 – 22.8

Optimising the activity of steel companies can be achieved by optimising processes and implicitly maximising the recycling and internal recirculation of generated waste, which has a high iron content; the waste generated can be minimised. Another way to minimise waste is to sell it to companies specialised in its processing (steel mill dust is processed to eliminate the zinc content; the extracted zinc is sent to the non-ferrous materials industry).

It should be mentioned that, in the steel industry, slag is one of the most well-known wastes and is generated in large quantities. The amount of slag generated depends directly on the processing aggregate used, the quality of the raw materials that make up the furnace charge, the quality and typology of the auxiliary materials used, and the type of steel processed. Table 3 shows the variations limits for certain sources of slag generation in the case of carbon/low alloy steel and high alloy steel in the electric arc furnace.

The proper management of residues/waste within a steel plant must focus on the application of advanced processing techniques (pelletizing, briquetting, agglomeration, direct reduction, etc.) aimed at exploiting, as much as possible, all useful components from the waste and residues generated.

Table 3

Quantities and sources of slag generation for certain types of steel [4]

Type of steel	Sources of slag generation	Quantity generated [kg/t liquid steel]
Low-alloy carbon steel	Slag from the oven	100 – 150
	Slag from the pouring pot	10 – 30
High-alloy carbon steel	Slag from the oven	100 – 135
	Slag from the pouring pot	30 – 40
	Slag from steel treatment	approximately 160

Separate identification and collection by category of materials, depending on chemical composition, particle size, or oil content, are necessary prerequisites to ensure the proper use of residues and waste within steel mills, without generating negative effects on production efficiency, product quality, and environmental protection [4].

The ferrous fraction of the different types of slag, dust, and iron and carbon-bearing sludges in gas treatment systems can be recirculated within the company by processing them (in pelletizing, briquetting, and agglomeration plants) and recovered in blast furnaces, electric arc furnaces, and basic oxygen converter.

The residues or waste generated in the steelmaking process in the electric arc furnace are found in the form [4]:

- Fine materials that tend to be recirculated through the agglomeration plant;
- Coarser materials that are used in the load of aggregates for the elaboration of cast iron and steel (blast furnace, electric arc furnace, converter).

The presence of high concentrations of compounds, such as alkali, heavy metals, and mineral oils in the residues generated and waste generated, determines the impossibility of recycling them within the steelmaking processes, as they damage the quality of the semi-finished product.

In some cases, certain residues/wastes are not economically useful (neither internally inside the facility nor outside), an aspect determined by the lack of useful elements and by the presence in high concentration of unwanted elements, so that within the residue and waste management activity, the elimination option is inevitable. The materials that usually require removal are those such as fine dusts from the cleaning of flue gases [4].

In industrial practise, steel companies with integrated production flow have their own certified landfill facilities, whereas other companies rely on external landfills. In all cases, landfills should be authorised to receive these types of waste [4].

In conclusion, appropriate management of production residues/waste that must be practised within steel companies should be based on the collection of waste materials by categories, chemical analysis to determine concentrations of undesirable elements (alkalis, chloride, heavy metals), their processing in specialised plants, internal recovery of residues in processed state, or sale to other sectors.

2.2 Case study: Management of secondary raw materials (scrap metal) and production waste within a steel company (steel mills) with an integrated production flow

Management of secondary raw materials (scrap metal) - The case study is conducted in a steel company that has an electric arc furnace with eccentric bottom tapping with a capacity of 100t; the main raw material used in the steel production process is scrap metal [15-17].

Scrap metal is delivered to the company by authorised suppliers, by rail or car transport. The unloading is carried out with the help of an electromagnet; subsequently, it is stored on concrete platforms. In the reception of scrap metal, the level of radioactivity (gamma radiation) is determined by means of a specialised system (located on the rail transport route, respectively, in the area where the vehicle weigh platform is located) [17]. The chemical composition of the waste is determined using an ORTEC gamma spectrometer [17].

For the storage of scrap metal and, implicitly, of its own and external metal waste, the company has two of its own warehouses located on its site. Of which one warehouse is not covered and paved, and the second is covered and consists of 6 pits with concrete platforms, located below ground level [15-17].

To eliminate the potential for contamination, scrap iron is sent to a sorting operation and, to facilitate its handling, cut with an oxyfuel flame. The cutting process applies to both scrap metal and its own steel waste. After the scrap iron has been sorted and cut to be brought to the appropriate dimensions for use/loading in the furnace, it is dosed and loaded into hoppers according to the recipes for composing the load.

The actions designed and applied by the company regarding the procedures for acquisition, collection, sorting, verification, storage of purchased scrap metal and its own waste, correspond to the recommendations of the BAT techniques and are presented in figure 4, which is identified following the reference study [17]. Due to production flow, (short-lived) storage of raw materials is carried out in specially designated places that cannot have any negative impact on the environment [17].

In the steel manufacturing process, auxiliary raw materials are also used, including fondants and fluidifiers for the formation of slag (lime, calcined dolomite, calcium fluoride), refractory materials, fuels, and ferroalloys. The operation of handling auxiliary materials is relatively simple, as they are kept in silos or airtight bags that are subsequently shipped and transported. All these materials are transported to buffer hoppers, located above the furnace, from where they are directly dosed into the aggregate [15].

The company has a system of storage and handling (reception, unloading) of materials (raw and auxiliary materials, technological waste), aligned with the norms provided in the BATs. Table 4 shows data on the quantities of raw materials and auxiliary materials managed by the company for one year. An important last aspect to mention concerns the scrap storage capacity that provides companies with a scrap metal reserve for 10 days [17].

Management of production waste (residues)

Within any steel company, a wide range of waste is generated; for each type of waste, it is necessary to determine exactly how it is managed according to the specifics of its characteristics. Table 5 shows the main types of production waste and the amounts generated in the different sections of the steel company over a year.

The collection of production waste is carried out depending on its physical condition, being temporarily stored inside the company, some of them (slag) being periodically evacuated in the dump, for processing and recovery. Ferrous waste such as scrap steel, mill scale, scrap metal, bar heads, etc., has a chemical composition like the material of origin, which is why they are properly collected and separated, and are temporarily stored for recycling in the steel production process [15].

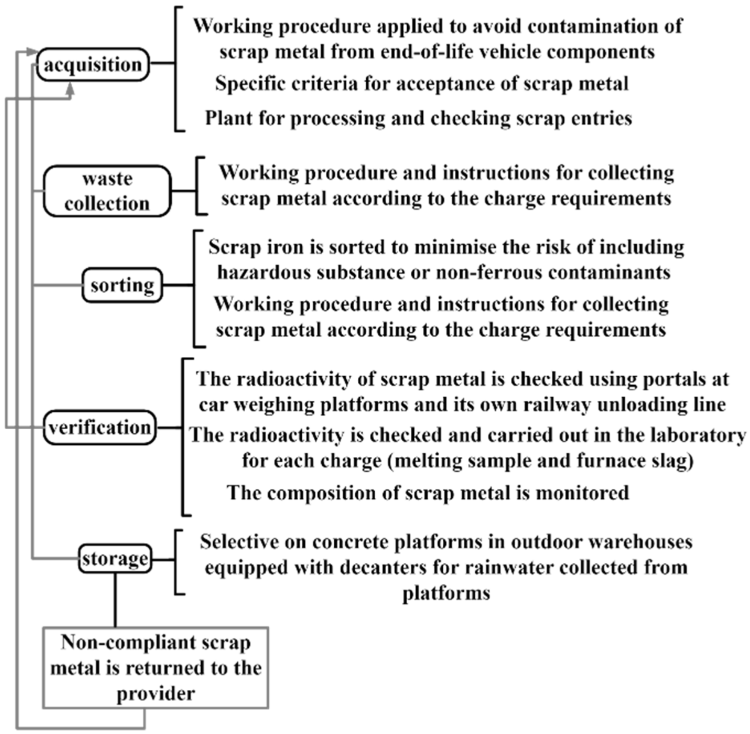

Fig. 4. Actions developed and implemented within a steel company on the management of secondary raw materials and the improvement of scrap utilisation [17]

Table 4

The main raw materials and auxiliary materials managed by the company [17,18]

Raw and auxiliary materials	**Quantity [t/an]**	**Storage mode**
scrap	260000	covered warehouses
lime	12475	open bunkers
coke	4800	open bunkers
calcined dolomite	1616	open bunkers
ferroalloys	3800	warehouse

Table 5

Quantities of production waste generated in the main sections [15]

Section	**Production waste**	**Quantity**
Steel mill	Slag oven	124.93kg/t liquid steel
	Solidified steel scrap	12.15kg/t
Continuous casting	Mill scale	2.4kg/t liquid steel
	Ferrous waste (Recoveries)	40kg/t liquid steel
Rolling	Waste scrap	39.28kg/t semi-finished product
	Mill scale	19.48kg/t semi-finished product

It is important to mention that the mill scale is a specific waste from continuous casting and rolling processes, which has iron oxides in its composition. This type of waste is detached from the steel ingot/semi-finished product during heating, handling and processing, subsequently separated by sedimentation and stored [15].

The furnace slag and the slag resulting from the secondary treatment process are tipped off the slag ladle and allowed to cool, then transported by car to the storage dump. This dump was leased to companies whose objective of activity is the recovery of metal (steel crusts) for use in the kiln load [15], and, respectively, the delivery of the nonmagnetic fraction to interested companies (road infrastructure construction industry, cement industry, etc.).

Another type of production waste recovered is dust from flue gas treatment that is stored in a brownfield hall of the company [15].

Following the manufacturing process, refractory materials are also generated, which are discharged with the help of special wagons in the slag dump [15].

Table 6 summarises the management of the main waste genered within the steel company. In conclusion, the ferrous waste generated is reintroduced into the technological process of steel production, and solid waste that cannot be recycled internally (mill scale, steel mill dust) because there are no proper processing facilities is taken over and recovered by specialised and interested economic operators.

Table 6

Ways of managing the different types of waste generated by the steel company [17]

Name of waste	Management mode	Storage mode	Recovery/ disposal method
Steel mill slag	The slag is evacuated, cooled, and transported to the existing slag dump	Intermediate warehouse (temporary storage); Dump	Processing by authorised economic operators for use in pig iron and steel production aggregates.
Dust from flue gas cleaning (steel mill dust)	Transported to a covered warehouse for recovery	Covered storage (temporary storage)	Takeover by authorised operators for recovery
Mill scale	After dehydration / drying, it is stored on concrete platforms and transported to a covered warehouse for recovery	Covered storage (temporary storage)	Takeover by authorised operators for recovery
Steel scrap (waste scrap, metallic scrap, crusts)	Direct collection at the place of generation	Temporary storage on company premises	Internal reuse
Refractory materials	Collection and temporary storage in the dump		Takeover by authorised operators for recovery

3. DISCUSSIONS AND PROPOSALS TO IMPROVE MATERIAL MANAGEMENT WITHIN THE STEEL PRODUCING COMPANY

The use of scrap metal (basic raw material in the steel industry) in the load charge can frequently cause delays in the supply flow (availability is reduced due to the durability of steel and the long service life of products made from steel), with scrap characteristics directly affecting the quality of the steel produced. For these reasons, it is recommended to diversify the metal load in the electric arc furnace, by introducing by-products (pellets, briquettes, iron sponge, agglomerate) made from small and powdery waste with iron content, own generated on the current steel production flow, as well as using historically stored iron-containing waste coming either exclusively from the steel industry but also from other adjacent industries such as the mining industry (sideritic waste), energy (thermal power plant ash), chemical (red sludge, pyritic ash).

Figure 5 presents ways to internally recover the own waste generated on the steel production flow in the electric arc furnace, a flow also practised within the company for which the case study was carried out. We know that the slag is processed, and the ferrous fraction belongs to the company to be used in the load of the elaboration aggregate, which was included in Figure 5 to apply the suggestions to any steel company. The proposed recovery processes (briquetting, pelletizing, agglomeration, and direct reduction) are practiced internationally; in our country they are predominantly practised the classical recovery processes (pelletizing, briquetting, agglomeration), whose costs are lower than the direct reduction process. We consider that the agglomeration process application is not recommended for the company on which the case study was carried out, given that in the past an agglomeration plant operated which was subsequently decommissioned for reasons of non-performance and non-adaptation to existing conditions [19].

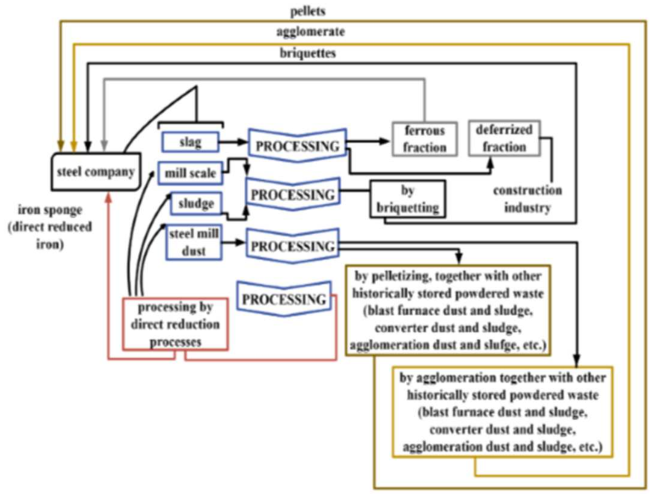

Fig. 5. Recommendation for the recovery of own production waste, according to the concept of circularity

The authors propose the following actions and measures to improve production waste management:

- The briquetting of mill scales waste and the use of briquettes in the load of the electric arc furnace due to the iron content, with the mention that the mill scale must have a low oil content.
- The steel mill dust can be taken over by authorised operators to remove the zinc content, and then the zinc content can be sold to the non-ferrous industry. Steel mill dust from which the zinc content has been removed can be taken over by a pelletizing company, and then the manufactured pellets have been sent to the steel mill for use in the load. In this way, a series of strategic partnerships were developed between the steel company and various operators authorised to process steel mill dust and other small and dusty waste (e.g., sludge).
- Development of win&win partnerships with other generators of iron-containing waste, management of historically stored iron-containing waste for waste processing, and delivery of the obtained by-products (pellets, briquettes) to the steel mill, to be used as raw materials.

By implementing the recommendations in Figure 5 and detailed above, any steel company could reduce the amount of scrap used, which is often the main cause of quality problems for steel semi-finished products.

The implementation of an integrated waste management system, applying the concepts of circular, green economy and sustainable development, within the steel society would contribute to reducing the level of pollution caused by industrial waste containing iron, which is why it is desirable to reintroduce the waste generated into manufacturing flows, applying the concept of closed loop recycling proposed.

The design and implementation of a variant of internal waste recycling that corresponds to the characteristics of the activities carried out in steel companies represents a future direction of research. In that variant, it is necessary to have only one type of user, namely the steel company and one or more processing and recovery companies. The existence of a single waste processing and recovery company is undesirable, as there is an increased risk of fluctuations in the production process due to delayed delivery of by-products made from waste or delivery of small quantities due to the poor production capacity of that recovery company. Thus, it is necessary for the steel company to collaborate with various processing and recovery companies to which to send the generated production waste, depending on the specifics of their activity and the characteristics of the waste. It is also considered necessary to establish supply modalities that meet the production requirements of both society and processors, starting from a supply chain approach from the perspective of the green, circular economy and sustainable development involving environmental protection and the conservation of natural resources [20].

4. CONCLUSIONS

Following the Best Available Techniques (BAT) study for iron and steel production, recommendations on material flow management within steel companies equipped with an electric arc furnace were identified and found the application of those recommendations within a steel company, conducting a detailed study of the activity of managing raw materials (scrap metal) and production waste. The purchase of scrap metal by the company was made only from authorised suppliers, which imposed specific quality requirements.

The company determines the radioactivity of scrap metal according to the requirements presented in the BREFs, and the storage is carried out on concrete platforms. Regarding production waste, the main slag, which is generated in significant quantities, is deposited in the landfill and subsequently processed, resulting in a ferrous fraction returned to the company for use in the steel production process and a deferrised fraction showing potential for recovery in the road and road construction industry, in the cement industry, etc. Most of the other waste (mill scale, sludge, steel mill dust) is stored in premises on the company's site, to be taken over by authorised operators for recovery, the company choosing the method of disposal and not internal reuse of this waste that has an intrinsic value determined by its content in useful elements (Fe, C), which favours its processing and use in the processes of elaboration of Fe-C alloys (steel, cast iron).

The limitations of the research carried out are highlighted in terms of difficulties in supplying scrap metal encountered by steel companies whose manufacturing flows allow the manufacture of steel based on waste; poor management of iron-containing waste within the generating society; reluctance of some steel producers to use by-products made from scrap iron in their load.

The future research directions envisaged consist in identifying the ways of waste management/recovery taken over by authorised operators and designing a strategic partnership scheme between generators (steel companies)/ managers (they manage historical waste storage facilities) - processors (companies specialised in processing and recovery of waste containing iron).

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Managementul fluxurilor de materiale în industria siderurgică. Studiu de caz: elaborarea oțelului în cuptorul cu arc electric

La nivel mondial activitatea tuturor societăților siderurgice trebuie să respecte recomandările prezentate în documentele Best Available Techniques Reference (BREF) aferente specificațiilor Best Available Techniques (BAT) emise pentru producția de fier și oțel. Din acest motiv în cadrul prezentei lucrării au fost identificate principalele specificații BAT privind managementul materiilor prime și a reziduurilor/deșeurilor de producție, aplicate societăților care produc oțel în cuptorul cu arc electric. Studiul de caz a fost efectuat pentru o oțelărie dotată cu un cuptor cu arc electric, în vederea prezentării managementului fluxurilor de materiale și deșeuri de producție, urmărind de asemenea și identificarea gradului de conformitate cu tehnicile BAT specifice. Potrivit celor constatate, s-au dezvoltat o serie de propuneri de îmbunătățire a managementului materialelor în cadrul societății producătoare de oțel pentru care s-a realizat studiul de caz.

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